

Study on Anneal Hardening of Carbon Steel

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I. Introduction

A phenomenon similar to anneal hardening of copper alloys can also be observed in carbon steel.

Cold worked carbon steel hardens in two stages on annealing, of which the initial hardening below 150°C is also called "strain age hardening", and it has been reasonably explained by Cottrell's mechanism. While the latter in the range of 150~350°C seems to be difficult to explain by adducing this mechanism¹⁾.

The study of the fundamental principle in reference to the latter, i.e., the secondary anneal hardening, has been made by different workers and led to many theories^{2) 3) 4)}, on the basis of which it appears to be impossible to account satisfactorily for its characteristics known up to the present. Amongst them, the precipitation theory which has been generally accepted, may be inappropriate by the reason that with high carbon steels electric resistance increases^{3) 4)} on annealing in the temperature range of this hardening after cold working.

In copper alloys as reported previously⁵⁾, α solid solution shows marked elastic after- and Bauschinger effects and also anneal hardening. On the other hand, in such polyphase alloys as aluminium alloys and steels, their solid solution itself exhibits little or no such effects⁶⁾. Anneal hardening is generally marked only in such alloys as showing pronounced these both effects, and in carbon steel, these both are still more prominent with increasing the carbon content^{7) 8)}. In accordance, the cause of secondary anneal hardening must probably be present at or near the phase boundaries between ferrite and cementite rather than within the ferrite, and furthermore, it is also to be expected that the hardening has a close relation with the Bauschinger effect in a similar manner to that in α brass. It is, thus, requisite first to study extensively these characteristics.

The anneal hardening of α brass is extremely sensitive to working conditions⁹⁾. With carbon steel, it is also similarly^{9) 10) 11)}, especially to secondary working differing in mode from the primary, producing the residual stress theory. But it may be unacceptable that residual stress affects the hardness. The presence of cementite and the interstitial solution of carbon atoms in carbon steel cause complication in many respects, the anneal hardening being

considerably different for different directions and properties to be measured.

The present investigation was carried out on carbon steels to study the characteristics and furthermore the nature of the anneal hardening.

II. Specimen and Method

Contents of impurities in carbon steels used in the experiments were listed in Table I.

Table I

Element	Si	Mn	P	S
Percentage	0.20~0.38	0.35~0.60	0.011~0.035	0.013~0.038

Anneal treatment for softening was performed by heating in the range of 30~50°C beyond the A_3 and A_1 points for 1 hour and then furnace cooling. Low temperature annealing was made by using both oil and tin baths, and heating time was 3~4 minutes, it differing for the heat capacity of specimen.

III. Characteristics of Anneal Hardening

1. Anneal Hardening of Carbon Steel

(1). Anneal hardening curve

In Fig.1 are shown anneal hardening curves for a series of plain carbon steels cold worked to various reductions, in which the hardness increases in two stages. The hardening below 150°C and that in the range of 150~340°C, will be called primary- and secondary anneal hardenings respectively, hereunder. In addition to these hardenings, a softening can be clearly observed at about 200°C with the low carbon steels, but with the higher carbon steels it becomes less marked. As shown in Fig.2, however, a specimen of the high carbon steel quenched from the temperature immediately below the A_1 point before cold working, shows a marked softening, it being likely that the softening is originated in the retrogression effect of the primary anneal hardening and thus that it is the more pronounced the greater the primary.

(2) Effects of carbon content and degree of cold working

Anneal hardening is largely affected by the carbon content (Fig. 3). As might be expected, the degree of primary anneal hardening decreases with the increase of carbon content, the decrease being considered to be in correspondence with that in volume of ferrite. This result, hence, may lead to the confirmation that the primary anneal hardening is based essentially on Cottrell's mechanism. Here, degrees of primary and secondary anneal hardenings were obtained in any case from the ratio of amount of increase

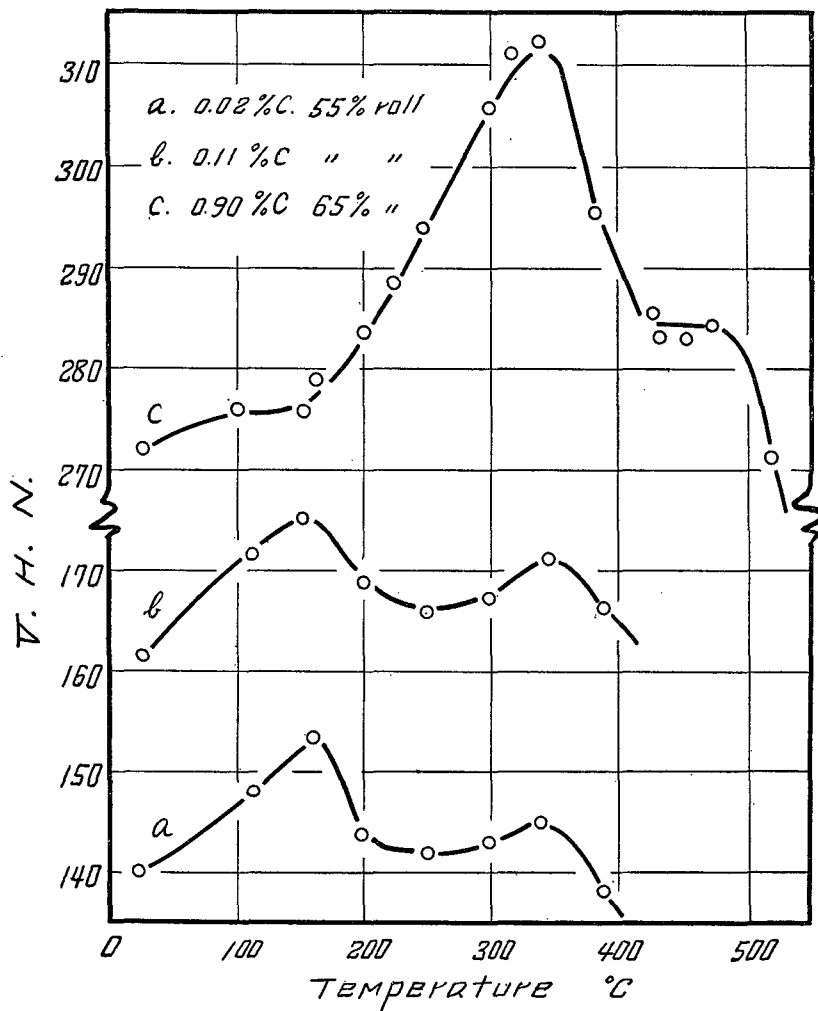


Fig.1 Anneal hardening curve

in hardness and initial hardness.

While, the degree of secondary anneal hardening is the more the higher the carbon content unlike the primary. This result strongly supports the view that the major contribution to secondary anneal hardening is associated with the phase boundaries between ferrite and cementite rather than the ferrite itself. In addition, the fact that the degree was constant below 0.2%C, leads to the presumption that the presence and magnitude of mutual interaction between cementite particles during cold working affect this hardening. The critical content at which the degree begins to abruptly increase, is different in shape and size of the particles¹²⁾, and the interaction

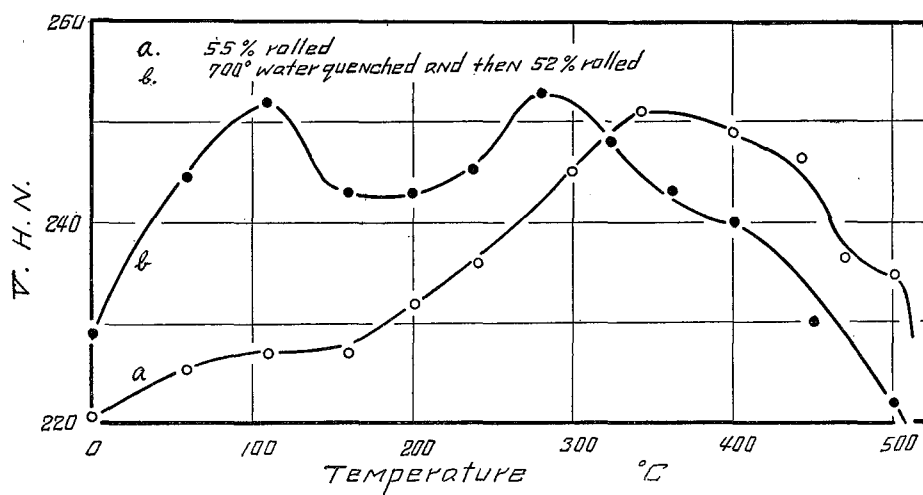


Fig. 2 Anneal hardening curve for 0.5%C steel quenched from 700°C and then rolled

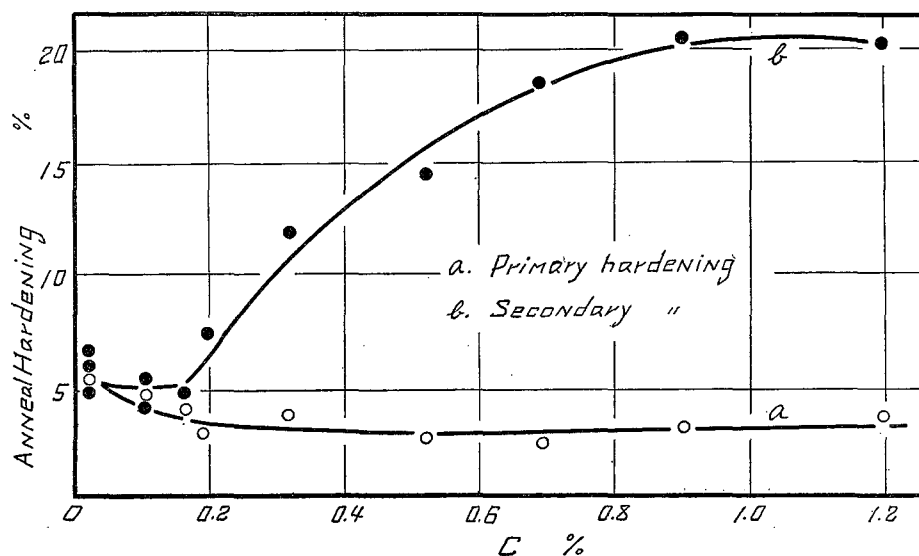


Fig. 3 Anneal hardening and carbon content in carbon steel rolled to 55% reduction

in a given steel is the greater the smaller the particles.

Fig. 4 indicates the relation between degrees of cold work and secondary anneal hardening in a 0.9%C steel, the degree increasing in two stages. The facts that the degree of secondary anneal hardening increased pronouncedly beyond about 40% reduction, and that it is much less in a coarse globular

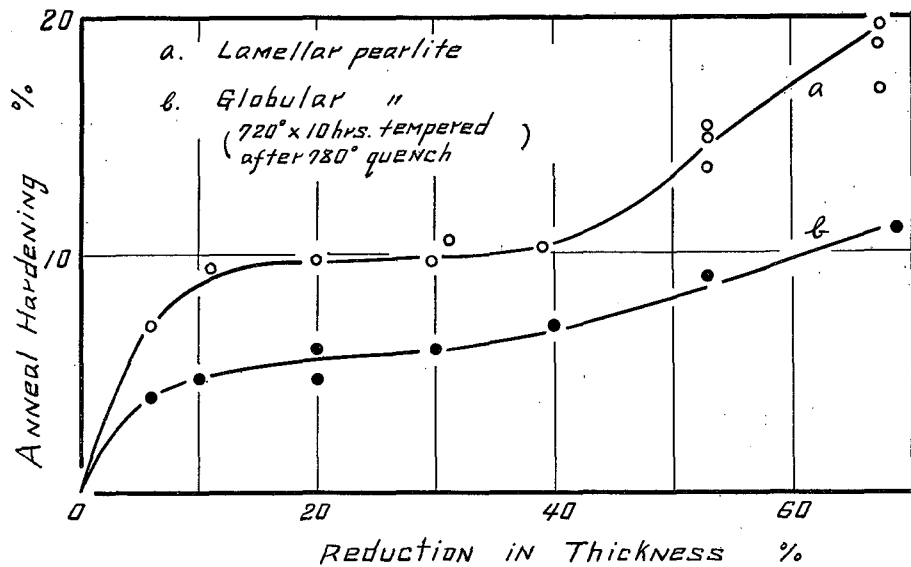


Fig. 4 Degrees of anneal hardening and cold rolling in 0.9%C steel

than in a fine lamellar structure as shown in the same figure, may lead to the considerations that beyond about 40% reduction cementite particles are markedly into fragments, and that the degree of secondary anneal hardening is closely dependent upon the area of phase boundaries.

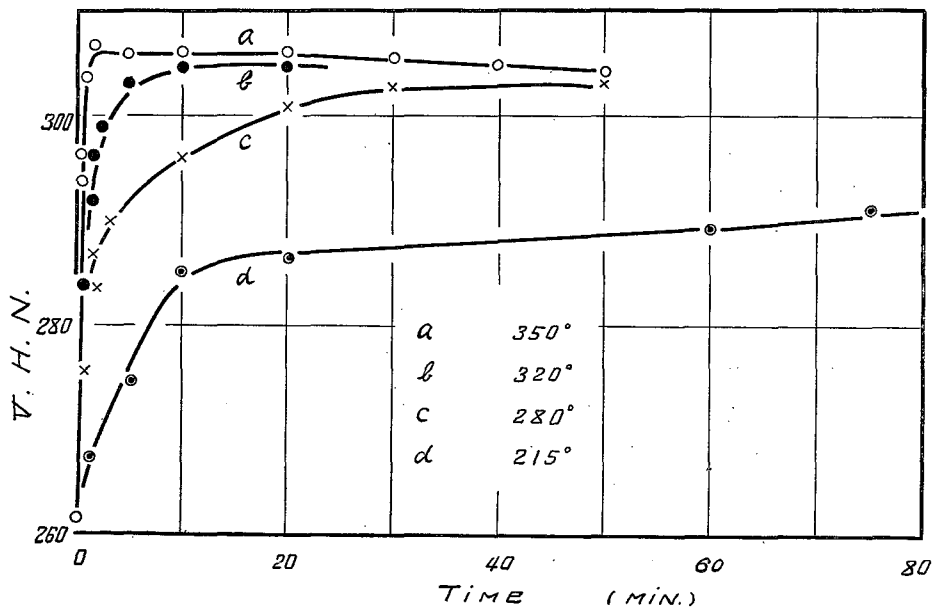


Fig. 5 Anneal hardening curves for 0.9%C steel rolled to 50% reduction

In Fig. 5 are revealed annealing time-hardness curves with a 0.9%C steel, the activation energy for the secondary anneal hardening obtained from this relation being about 27000 cal/mol. This value is much higher as compared with that of the primary, say, about 18000 cal/mol, and in addition, it seems to be irrespective of the carbon content unlike in the case of tempering of martensite.

2. Bauschinger Effect and Anneal Hardening

(1) Change of yield strength by low temperature annealing

A hardening would be expected to be accompanied by a rise in yield point, but in α brass, the result contrary to this expectation was obtained⁵⁾. To ascertain this relation in reference to carbon steel, measurements of yield point were performed by tension, for which Amsler's universal testing machine was employed.

Relation between change of yield point in the same direction as the primary tension and annealing temperature is given by curve (b) in Fig. 6. Yield point is raised greatly within the temperature range of the primary anneal hardening. While, it shows a dissimilar trend to that of the secondary, and especially in lower carbon steels, there is no rise in yield point corresponding to the secondary, but rather lowering. Hence, it may be considered that the primary anneal hardening can be reasonably explained by the mechanism already proposed, say, of locking of dislocations by solute atoms, on the other hand, the secondary can not by such a mechanism.

However, the rise in yield point can be observed only when it is measured under a stress of different type or direction from that of prior working, this rise being probably due to the elimination of Bauschinger effect as described later.

(2) Bauschinger effect

Experiments on Bauschinger effect were carried out by torsion, which was adapted to a reversal of stress. The specimen was supplied in the thin walled hollow cylinders with the same dimensions as that in the case of α brass*, in order to homogenizing the distribution of applied stress.

Specimens were first twisted followed by low temperature annealing at zero load, and then re-twisted in the direction reverse to prior working. The results with a 0.9%C steel are given in Fig. 7. As shown by curve (a), which concerns a specimen without low temperature annealing, the steel

* : Reference (5) Fig. 21

shows a marked Bauschinger effect.

The yield point in the reverse direction is raised by the annealing (curves b and c in Fig. 7). Temperature dependency of the ratio of yield point λ/λ_0

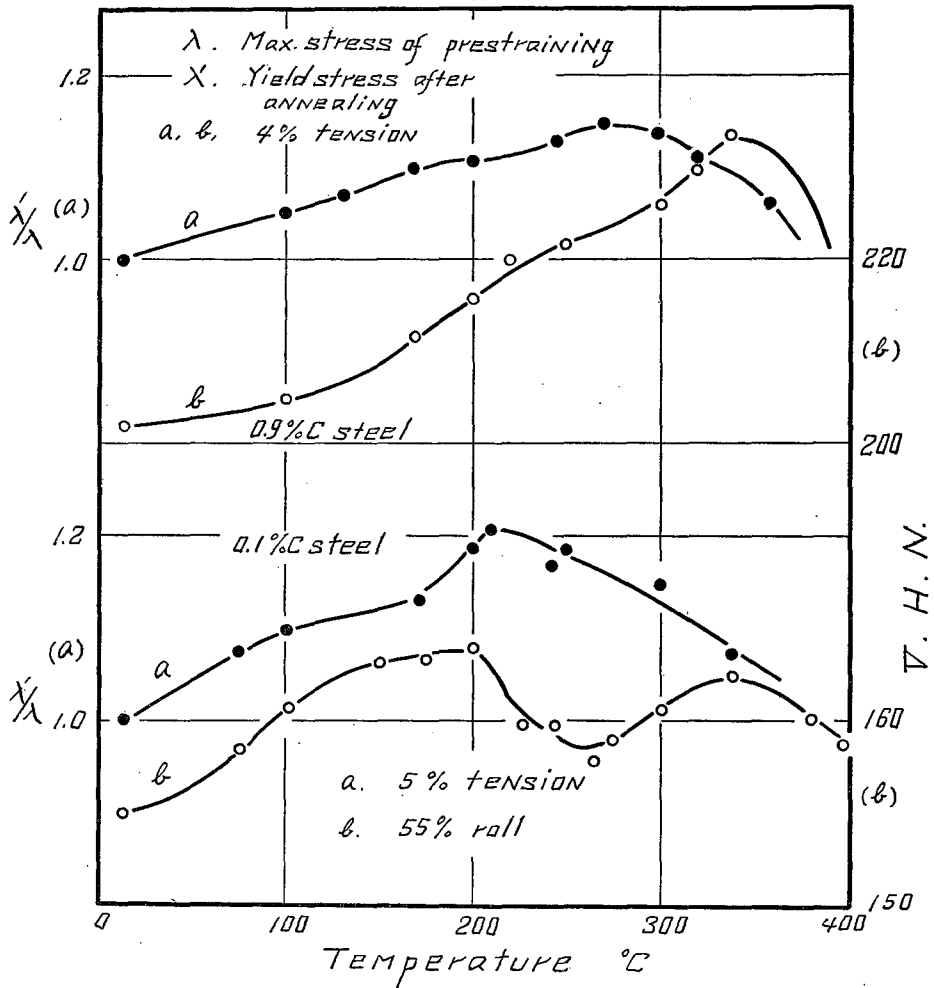


Fig.6 Change of yield strength of extended specimens with annealing temperature

is revealed by curve (a) in Fig.8, the shape of the curve bearing a close relationship to that of anneal hardening curve (curve b), and it differs widely from that of the change of yield point in the working direction. Here, λ_0 and λ are noted in Fig.7.

As shown in Fig.9, the higher the degree of prior torsion the more marke

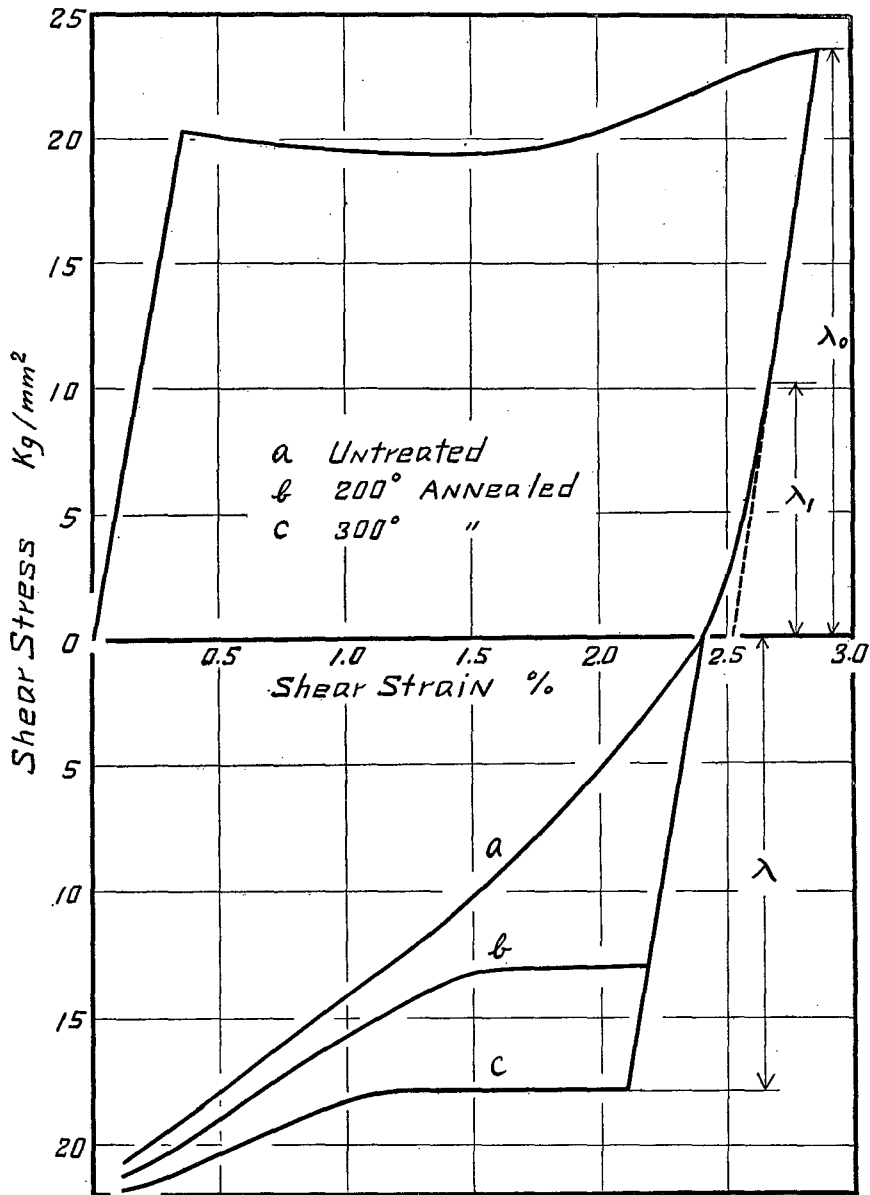
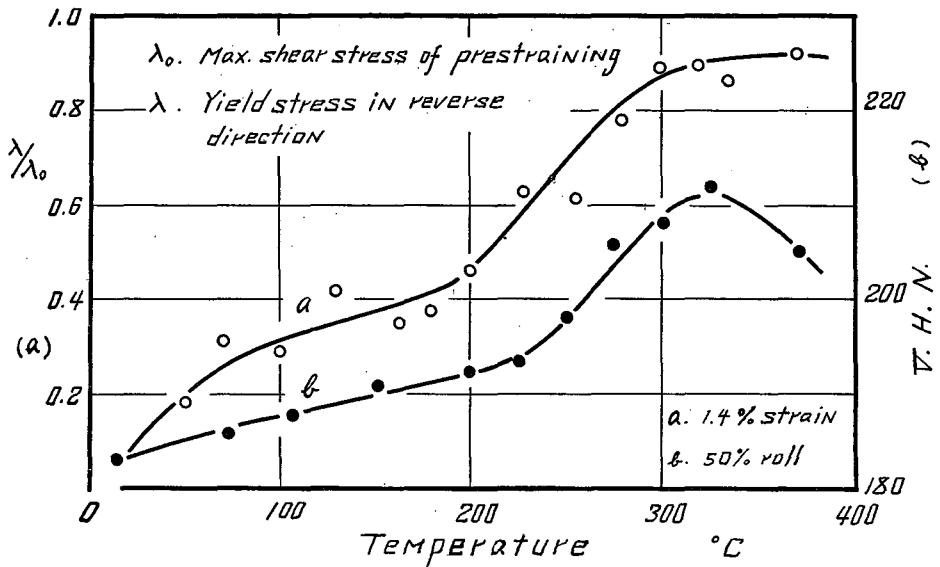
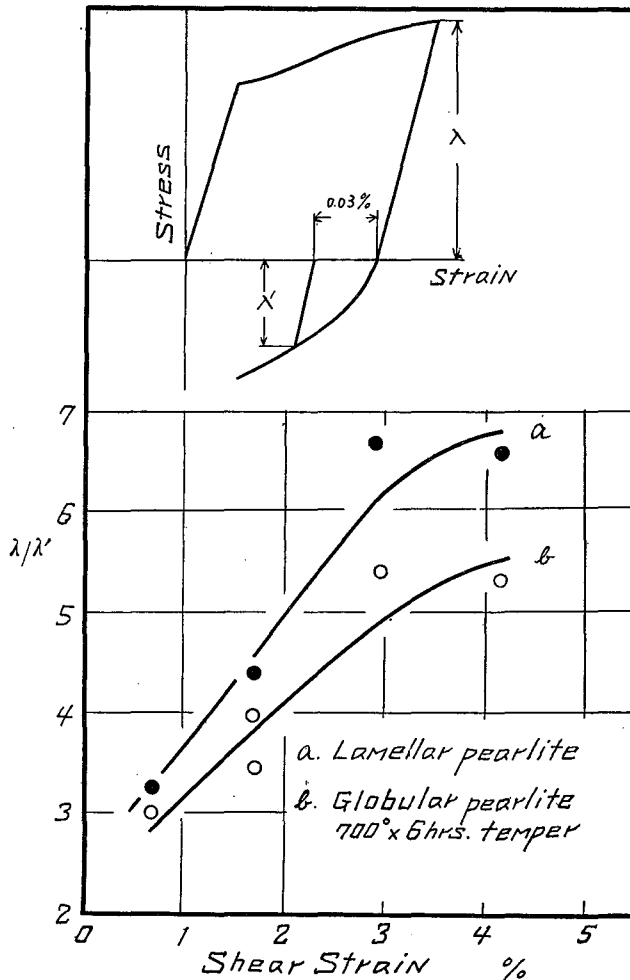


Fig.7 Torsion stress-strain diagram of 0.9%C steel

the Bauschinger effect, and in addition, the degree of this effect λ/λ' is much less for a coarse globular than for a lamellar structure, this trend being in good agreement with that in Fig. 4. Here, since the degree of Bauschinger effect is hard to measure in such alloys as showing a marked effect, it was obliged to represent by the ratio of the maximum



↑ Fig. 8 Ratio of yield strength and annealing temperature in 0.3% C steel



stress applied in the direction of prior torsion and the stress corresponding to permanent strain 0.03% in the reverse direction as shown at the upper part of Fig. 9.

(3) Degree of cold work and anelastic effect

For obtaining more exact informations on the subject, anelastic effect in heavily worked specimens was studied.

← Fig. 9 Degrees of Bauschinger effect and cold work in 0.9% C steel

Experiments of Bauschinger effect in the range of higher strains are extremely difficult. So, the anelastic deformation being considered to commence upon unloading after prior working at the point where the straight line begins to curve, the ratio λ_1/λ_0 was taken to represent the degree of anelastic effect. Here, λ_0 and λ_1 were noted in Fig. 7. The ratio is very small in such alloys as showing little or no anneal hardening. Experiments were made by tension at room temperature (18~24°C).

The results obtained with a series of carbon steels are shown in Fig. 10, which indicates that the shape of the curves is conformable to that in Fig. 4. Furthermore, as given in Fig. 11, the ratio increases with increasing

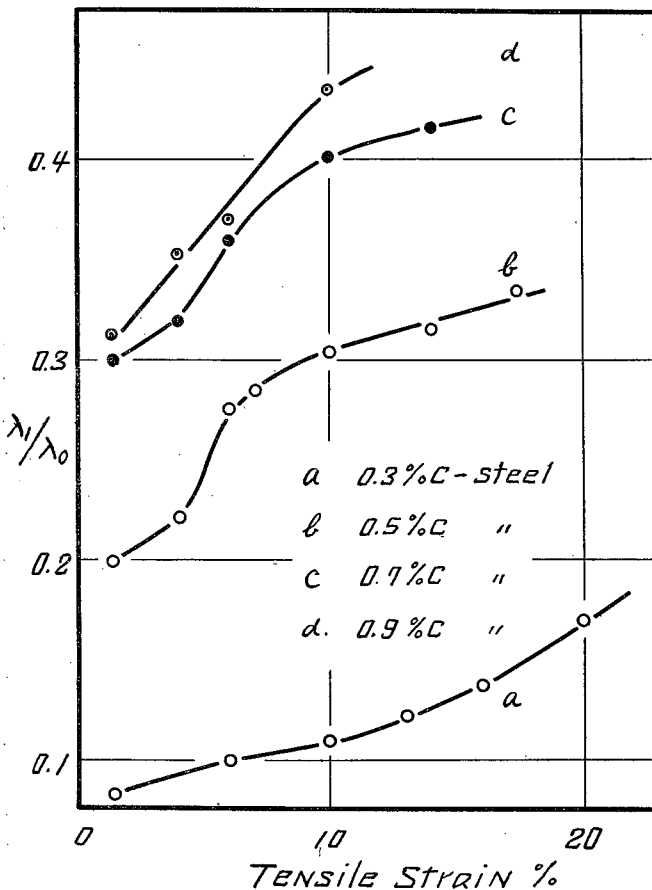


Fig. 10 Anelastic effect and tensile strain

the carbon content in a similar manner to that shown by curve (b) in Fig. 3.

The results so far obtained with reference to secondary anneal hardening were nearly the same as those in α brass⁵⁾, showing that there is a hardening also in carbon steel originated in the elimination of Bauschinger effect even without a rise of yield point in the working direction. However, a slight rise of yield point was observed in the temperature range somewhat lower than that of secondary anneal hardening, as shown by curve (a) in Fig. 6, while, this rise is absent in α brass.

It is, hence, considered

that the mechanism of secondary anneal hardening of carbon steel is even more complicated. This will be stated later.

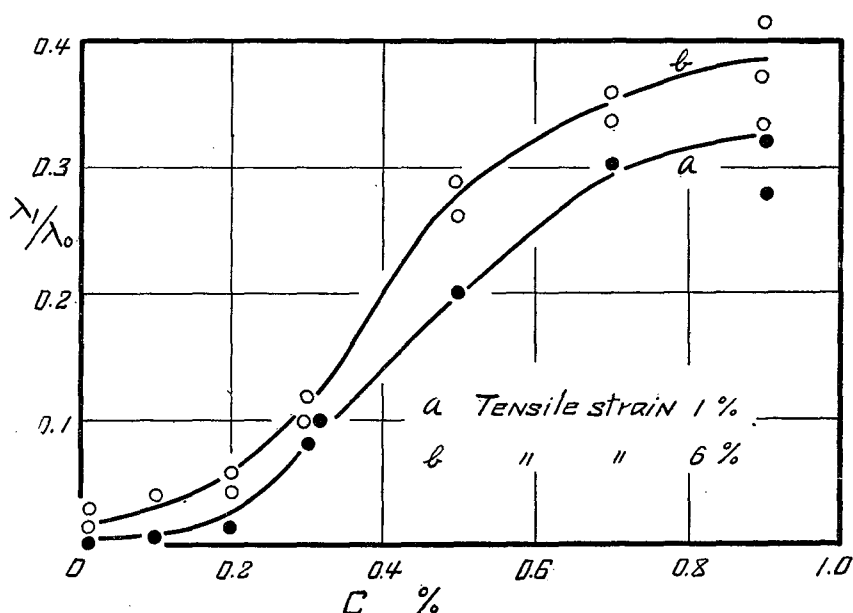


Fig. 11 Anelastic effect and carbon content

3. Consideration

(1) Unlike copper alloys, in which α solid solution itself exhibits marked Bauschinger effect and anneal hardening, in such polyphase alloys as aluminium alloys and carbon steel their solid solution itself does not pronouncedly show these phenomena. In accordance, it is presumed that in these alloys, the major contribution to these phenomena is associated with the phase boundary rather than the solid solution itself, and more that interstitial solution of carbon atoms into ferrite causes a more further complication in the mechanism of secondary anneal hardening than that in aluminium alloys.

(2) In α brass, thermoelectric force, thermal dilatation and anneal hardening are closely dependent upon the mode of cold working⁵⁾, that is, the modes in the descending order of the magnitude of degree of anneal hardening are (1) drawing, (2) rolling, (3) compression, (4) tension. This order is also considered to be in correspondence with that of the magnitude of friction between material to be cold worked and tool. On this basis it was presumed in the previous paper⁵⁾ that both this friction and marked anisotropy in the mechanical properties¹³⁾ brought about a pronounced anneal hardening.

While in carbon steel, the effect of mode of cold working is far less, although there is a report¹⁴⁾ showing its presence. It is, hence, considered

that the deformation structure is mainly associated with the difference of mechanical properties between ferrite and cementite rather than the friction.

As deformation proceeds, dislocation loops are created around cementite particles, and they cause back stresses. In addition, vacancies generated by climb up of dislocations at phase boundaries, may distribute in an anisotropic manner. Such a deformation structure is considered to bring about an anisotropy in anelastic effect, and also to be dependent upon distribution, shape and size of cementite particles.

Upper yield point of carbon steel can not be detected in the as-cold worked state. It becomes observable in the working direction by annealing at the temperature range of primary anneal hardening (about 100°C), but not in the reverse direction even at 200°C . Such an anisotropic recovery has been considered to be due to the action of macro-stress¹⁾, but since the stress also acts to the working direction, this consideration may not be reasonable. Then, the deformation structure, in which an anisotropic deformation is easy to occur, and the effect of carbon atoms on the structure must be thought together. These will be described in a later section.

(3) The degree of secondary anneal hardening remains constant below $0.2\%\text{C}$ as shown by curve (b) in Fig.3, and the presence of only a few cementite particles does hardly affect the derangement of stress distribution in the ferrite during cold working.

Secondary anneal hardening, however, becomes pronouncedly marked as the carbon content increases in the range above the critical value, indicating that in this range cementite particles may interact mutually, that is, the distance between the particles becomes moderate to allow the formation of dislocation loops. When the distance is too small or too large, it appears to be difficult, in any case, to create a large number of dislocation loops around them.

(4) When the hardness of carbon steel is measured at higher temperatures, it increases considerably at about 250°C , this hardening being called "blue brittleness", which has been generally explained to be due to a relatively active diffusion of carbon atoms. Since its temperature is somewhat lower than that of secondary anneal hardening, and in addition, it is more marked in low carbon steels¹⁾, it may be inappropriate to adduce this mechanism to the explanation of secondary anneal hardening, which is marked in high carbon steels.

The changes in electric resistance during cold working and on subsequent annealing are different in the carbon content^{3) 4)}. The resistance decreases on annealing in the range of $200\sim 300^{\circ}\text{C}$ after cold working in low carbon steel, on the contrary, it increases with high carbon steel. Since the resistance in a given steel is closely dependent on distribution, shape and size of

cementite particles, it may be difficult to elucidate the cause of this difference. It may, however, not be unreasonable to presume in the followings. The increase in electric resistance observed on high carbon steel, is not attributed to the precipitation of carbide. Furthermore, it is possible to correlate the vacancies created during cold work with the solubility change of foreign atoms to ferrite. The hydrogen saturation increases as cold work proceeds, and it is the more the higher the carbon content⁴⁾. Hence, carbon may also behave in a similar manner. Unstable particles of cementite decompose during annealing at about 250°C so that carbon atoms dissolve into such locations in ferrite as showing high concentration of vacancies, causing increase in electric resistance and relaxation of internal stresses around the cementite particles and vacancy aggregates.

4. Conclusion

Study on the anneal hardening of carbon steel was carried out and the results obtained are as follows.

(1) Anneal hardening occurs in two stages on annealing after cold work, of which the primary hardening at about 100°C takes place within the ferrite and it may be reasonably explained by Cottrell's mechanism. While, the secondary in the range of 150~340°C becomes marked with increasing the carbon content, showing that this hardening is associated with the phase boundaries, and more that it may be affected by arrangement, shape and size of cementite particles. In brass, α solid solution itself gives rise to marked Bauschinger effect and anneal hardening, while in carbon steel, these phenomena are not so pronounced in the ferrite.

(2) As shown in Fig.6, secondary anneal hardening was not accompanied by a rise in yield point, which was measured after low temperature annealing under a stress of the same kind and direction as that of prior working. In addition, high carbon steels exhibit a marked Bauschinger effect, the elimination of which shows a similar trend to that of anneal hardening. Thus, it is likely that the secondary is chiefly due to the elimination of Bauschinger effect, as in the case of α brass.

IV. Some Phenomena Related with Anneal Hardening

The anneal hardening of carbon steel in the range of 150~340°C, closely resembles that of α brass. However, the latter is a change within a simple solid solution, while the former is that at the phase boundaries rather than within the ferrite.

When a cold drawn carbon steel is slightly extended after annealing at

300°C, it becomes tough¹¹⁾, this change being similar to the work softening in α brass*. Also, a slight application of tensile stress to a compressed specimen, brings about a softening⁹⁾, which is exactly an opposite change to the secondary work hardening in α brass**.

The facts that when a tempered high carbon steel is slightly cold worked, it softens markedly¹⁵⁾, and subsequently it shows a considerable anneal hardening, can not be observed in other alloys.

The anneal hardening of carbon steel is accompanied by such peculiar phenomena, and thus, the author wishes first to make the principle of anneal hardening more definite by studying these attendant phenomena.

1. Retrogression Effect

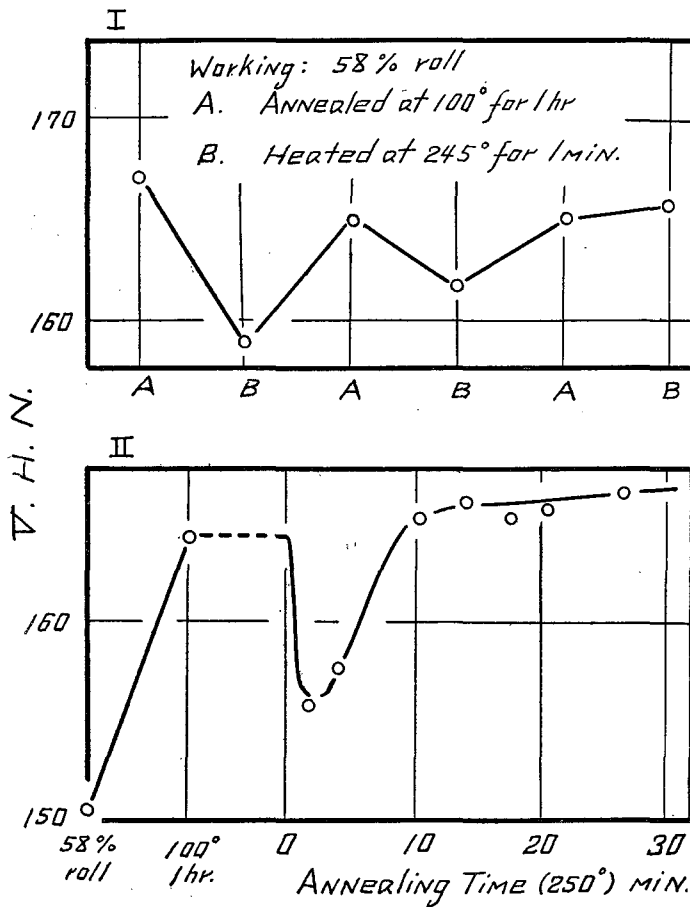


Fig. 12- II reveals a retrogression effect of a low carbon steel. When a specimen was annealed at 250°C for the duration shown in the abscissa after annealing at 100°C, it initially softened and then hardened. This softening is accompanied by an increase in thermo-electric force***, and it is considered to be due to a dispersion of carbon atoms from dislocations. Since, however, during retrogression treatment the disappearance of vacancies and the relaxation of internal stresses

Fig. 12 Retrogression effect of 0.1%C steel

* Reference (5) Fig.38

** Reference (5) Figs.40, 41

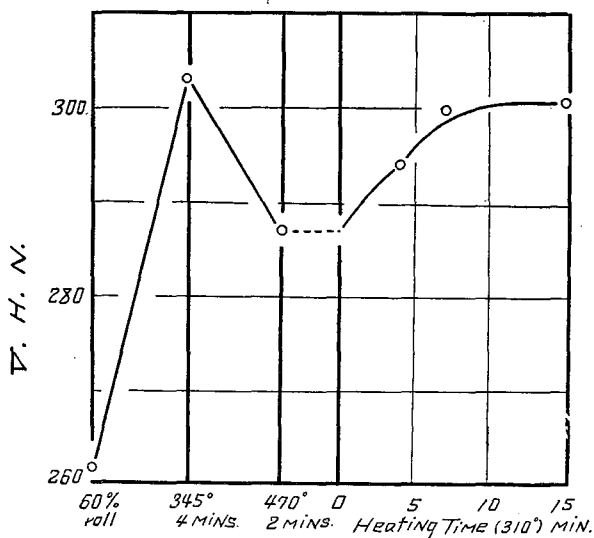
*** Reference (5) Fig.17

as the process of recovery go on without rest, the retrogression effect becomes less marked, when retrogression treatment and low temperature annealing are repeated (Fig.12-1).

The retrogression effect can also be observed after the secondary anneal hardening, as given in Fig. 13. This effect, however, was hard to detect and showed little or no repeativity, it being presumed to be due to a change in mutual interaction between lattice defects, since the temperature of retrogression treatment is probably in correspondence to that of polygonization as in the case of α brass.

2. Work Softening

In Fig. 14 is represented the work softening. When a slight working



of the same mode as that of prior working is applied secondarily after anneal hardening treatment, softening occurs similarly to the case of α brass*. It may, therefore, be considered that by such a slight application, an anneal hardened specimen is forced to come back in the state before low temperature annealing, and as the result softening takes place.

As given in Fig. 15, Bau-schinger effect becomes again marked by a slight secondary working. Namely, when low temperature annealing is made after the prior torsion, the effect is removed (curve a), but when a specimen is re-twisted in the direction of prior torsion after low temperature annealing under zero load, it becomes again pronounced (curve b). Here, the measurements were carried out in the same manner as described with reference to Fig. 7.

* Reference (5) Fig. 38

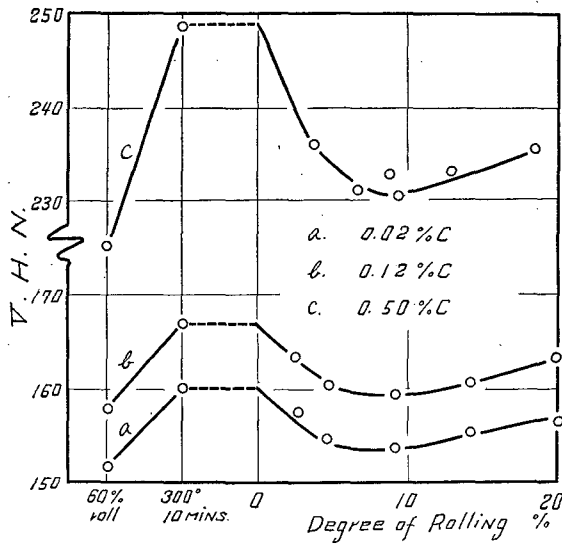


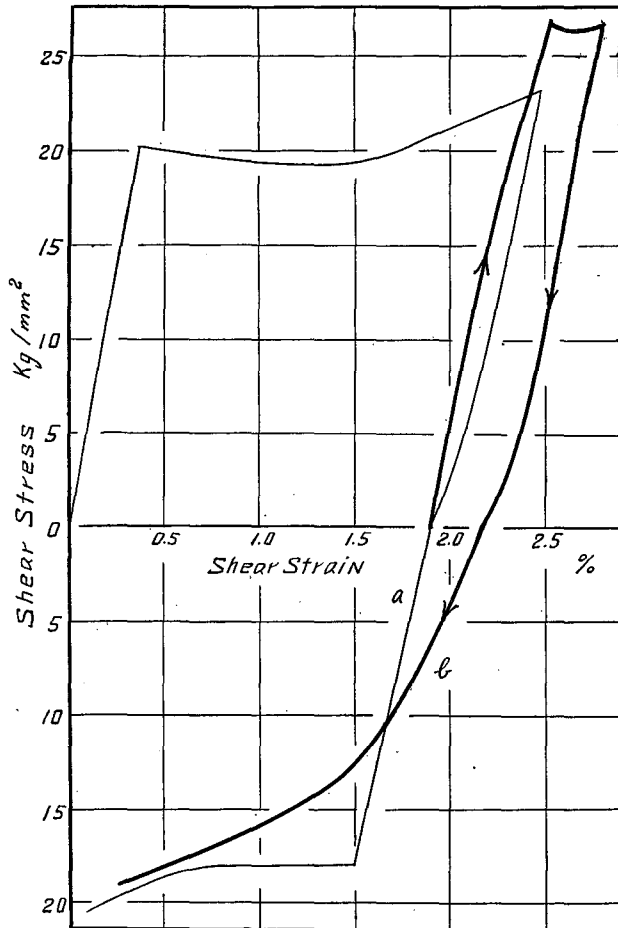
Fig. 14 Work softening curves

the primary and secondary workings are of the same mode, but when they are different, it becomes rather complicated.

In Fig. 16 are shown rolling degree - hardness curves for severely drawn specimens of carbon steels. With the progress of such a different mode - secondary working, specimens first hardened and then softened. This hardening will be called "secondary work hardening".

This hardening is very

Fig. 15 Torsion stress-strain diagram of 0.9%C steel



By such an application thermoelectric force returns completely to the value before low temperature annealing*, but the anneal hardening of such a specimen is marked below 200°C similarly to that shown by curve (a) in Fig. 21, unlike in the case of a primarily cold worked specimen.

3. Secondary Work Hardening

No special question arises when

* Reference (5) Ffig. 15

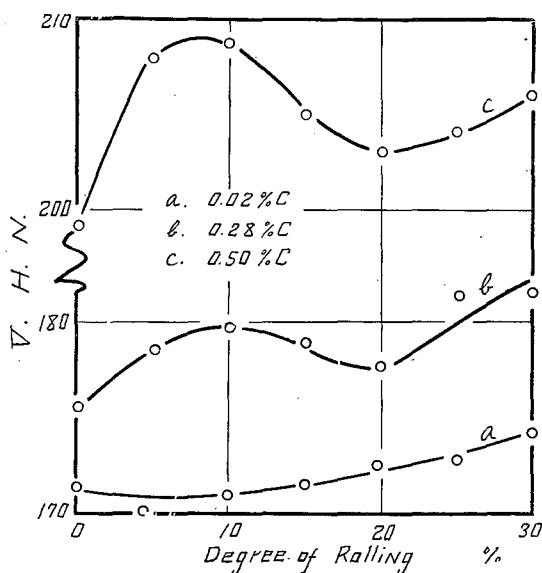


Fig. 16 Degree of rolling and hardness of carbon steels drawn to 64% reduction

primary working is heavy, the degree of secondary work hardening is nearly equivalent to that of the softening. It is likely that when the primary and secondary workings are severely made, in any case, the structure specific to the mode of cold working is obtained, it being in the softened state, and in the intermediate stage where the as primary-worked structure transforms to the secondary, the structure is in the hardened state.

There has been some reports^{9) 16)} that a softening was induced by an application of different mode- secondary working, unlike the results stated above. In α brass⁵⁾, the modes of cold work, in the descending order of the magnitude of degree of anneal hardening are, (1) drawing, (2) rolling, (3) compression, (4) tension. When the secondary working is of a mode lower in the above order than the primary, secondary work hardening will appear, while, when vice versa, softening takes place in some case as the result of the promotion of anisotropy in anelastic effect, but of rare occurrence. It may be necessary to pay attention on measurements of secondary work hardening that this hardening is difficult to detect when a specimen is aged or deformed mechanically before secondary working, because work softening occurs during secondary working.

In Fig. 17 is shown the secondary work hardening of 8% Al-Cu alloy, which exhibits a marked anneal hardening. When a specimen was extended after cold rolling, it hardened conspicuously, and thereafter softened by a

small in low carbon steel, but becomes marked with increasing the carbon content. However, there is an important difference between α brass and carbon steel, that is, in the former the degree of secondary work hardening is approximately equal to that of anneal hardening, while in the latter the secondary work hardening is less marked.

On continued working after secondary work hardening, softening occurs. In carbon steel as shown by curve (c) in Fig. 16, the softening is observed in the range of 10~20% reduction of rolling. In α brass, when the

slight application of cold working of the same mode as that of primary working. An interesting observation is the findings that this softening is of the same kind as the work softening observed after anneal hardening treatment, and that tensile working made after the primary rolling shows a similar effect to that of low temperature annealing. It is, therefore, inferred that anneal hardening and secondary work hardening are induced by the same cause, and that anneal hardening can be obtained not only by low temperature annealing but also by mechanical treatment. That is, anneal hardening and secondary work hardening are similar phenomena due to destruction of the deformation structure. They are dissimilar only in that in the former the destruction is caused by internal stress and thermal diffusion, while in the latter it is caused by forced deformation.

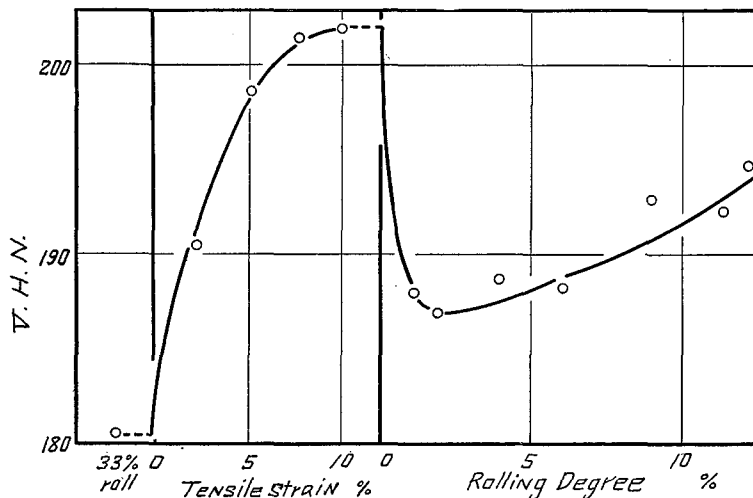


Fig. 17 Secondary working and hardness of 8% Al-Cu alloy

The anneal hardening of carbon steel can also be obtained by a mechanical treatment. But the secondary work hardening is less marked as shown in Fig. 16, and when a specimen in secondary work hardened state is annealed at low temperature, it considerably hardens. This behavior is rather widely different in trend from that in the case of α brass*, and this will be described later.

4. Work Softening of Tempered Steel

In Fig. 18 are shown hardness-rolling degree curves for a 0.9%C steel quenched from 800°C and then tempered at the illustrated temperatures,

* Reference (5) Fig. 43

indicating that work softening in the earlier stages of cold rolling becomes marked as tempering temperature is lowered, and that when a specimen is annealed at low temperature after slight rolling, it hardens nearly up to the hardness before the cold working as given by curve (a').

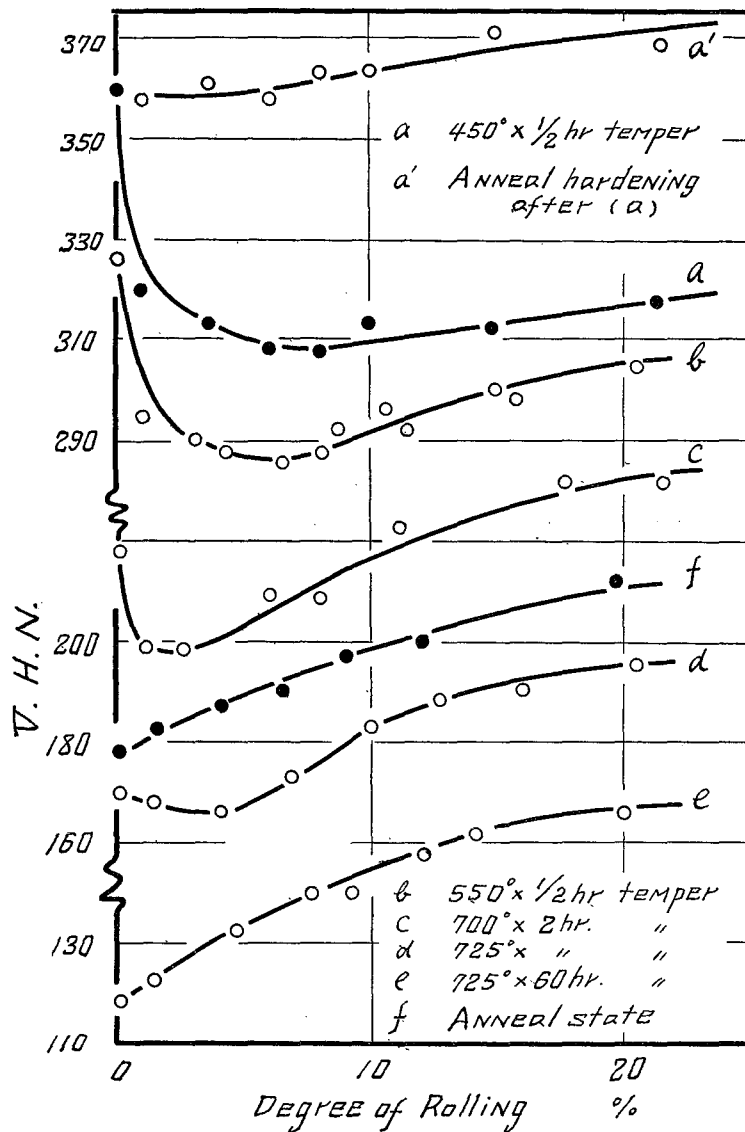


Fig. 18 Work softening curves of 0.9%C steel quenched and tempered

As tempering temperature is raised, cementite particles coarsen and vacancies disappear. By curve (a) in Fig. 19 is shown the relation of density versus

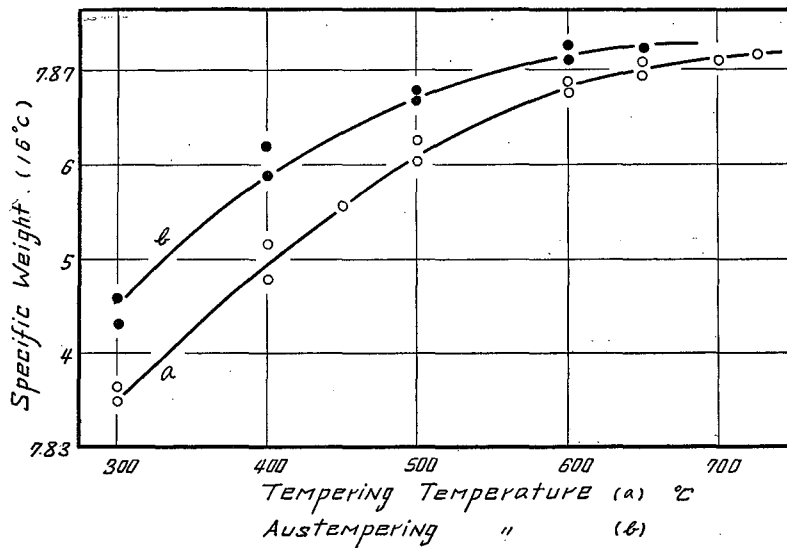


Fig. 19 Tempering (a) and austempering (b) temperatures and density of 0.9%C steel

tempering temperature. Here, tempering time is in any case 30 minutes, and the method determining density is based essentially upon measuring the volume of the water being identical to that of specimen. The fact that the lower the tempering temperature the smaller the density, is probably due to various factors, of which vacancies included in large number in quenched steel seems to play a considerable part in the change in density.

Curve (b) in the same figure shows the change in density of specimens isothermally transformed at various temperatures so as to obtain the same hardness as that in the case of tempering. Density is larger in specimens isothermally treated than those tempered, and the degree of work softening is less in the former. It may, therefore, be inferred that vacancies contribute to the work softening and anneal hardening.

Fig. 20 represents the relation of total surface area of cementite particles versus degree of anneal hardening in a 0.9%C steel tempered at various temperatures and then 10% rolled. Within the range of measurements, the finer the cementite particles the higher the degree of anneal hardening.

The work softening of tempered steel may not be interpreted merely in terms of mobility of locked dislocations. Specimens tempered at higher temperatures undergo discontinuous yielding, and in such cases the upper yield point was observed. At lower temperatures, however, discontinuous yielding does not take place, and the critical temperature rises as the carbon content increases¹⁷⁾, say, 450°C and 550°C in 0.4%C and 0.9%C steels respectively.

In addition, it was confirmed from the measurements on tensile stress-strain relationship of a tempered carbon steel that there was nothing unusual about this relationship. The tensile stress increases progressively from the start of straining, and in fact, the work hardening, as judged from the changes in tensile stress, increases as the microstructure becomes finer, indicating that the work softening effect is also directional.

An outstanding feature of anneal hardening of carbon steels tempered and then cold worked, is that when the tempering temperature is considerably low, the hardening is pronounced below 200°C and as the temperature rises it becomes marked in the range of 250~340°C (Fig. 21)

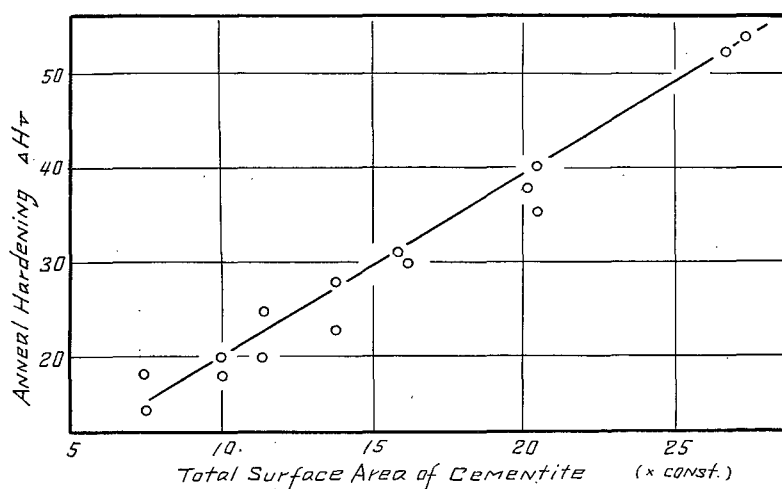


Fig. 20 Degree of anneal hardening and size of cementite particles of 0.9%C steel tempered and then 10% rolled

V. General Discussion

1. Anneal hardening of carbon steel occurs in two stages, of which the primary anneal hardening observed at about 100°C, may be explained by Cottrell's mechanism. While the secondary in the range of 150~340°C, is considered to be impossible by this mechanism.

Amongst theories already proposed for explaining the secondary anneal hardening, those of precipitation¹⁸⁾ and residual stress⁴⁾, etc, seem to be hardly acceptable by the following reasons.

(1) As described already with reference to Fig. 6, no rise of yield point corresponding to the secondary anneal hardening could be detected upon measuring under a stress the same in kind and direction as that of

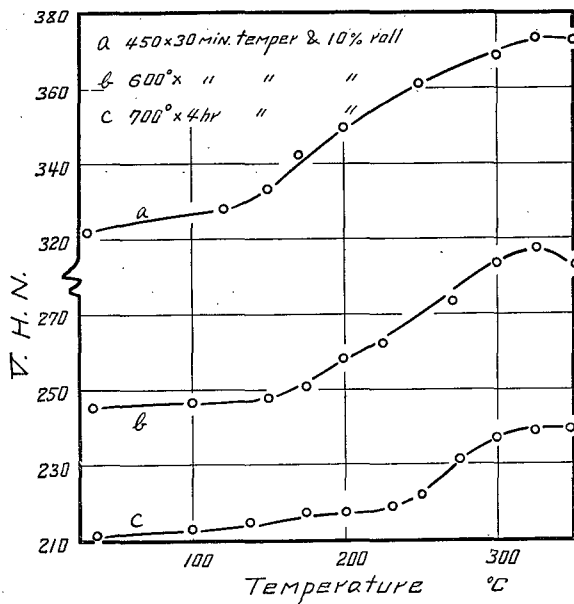


Fig. 21 Anneal hardening curves for 0.9%C steel tempered at various temperatures

prior working. Therefore, a theory being merely on the basis of a rise in yield point may not be capable of explaining this hardening. Anisotropy in mechanical properties must be considered for the elucidation.

(2) The secondary anneal hardening is more marked with the higher carbon steels, indicating that this hardening takes place near the phase boundaries between ferrite and cementite. While, the primary and quench age hardenings generally occur within the ferrite, these being essentially different from the secondary.

(3) The secondary anneal hardening is brought about

not only by low temperature annealing but by a mechanical treatment. This hardening, hence, does not necessarily need annealing.

(4) In tempered steel, a slight application of cold work induces softening, probably showing that this softening is essentially the same in cause as the work softening in anneal hardened specimen, and thus that anneal hardened state can also be obtained by tempering, that is, even without cold working. 2. When dislocation lines are linear, internal stresses promote the movement of dislocations in some locations but they prevent in other locations. Since the resultant of such stresses in a mass must be zero, their effect are cancelled as a whole. In accordance, for the explanation of the removal of Bauschinger effect without a marked change of yield strength in the working direction (Figs. 6 and 8), curved dislocations must be considered.

As deformation proceeds, dislocation loops are created around the particles, and their number is dependent on the properties of particles. The loops cause back stresses, by which Bauschinger effect is considered to be brought about. In carbon steel, cementite particles and vacancy aggregates or stacking faults may contribute to this effect.

The presence of cementite particles gives rise to the derangement of stress distribution in matrix and the mutual interaction. As the results, they rearrange

so as to decrease the resistance to plastic flow, and in addition, the structure around the particles becomes anisotropic. Also, the distribution and shape of vacancy aggregates created by climb up of dislocations at phase boundaries, are directional. Thus, cementite particles and vacancies segregated around them show anisotropic arrangement and shape depending on work condition, causing back stresses and hence a marked Bauschinger effect to appear in the material.

Such a structure, once destroyed by some stimuli, will have its anelastic effect eliminated, and hardening sets in. Internal stress is one of them. α brass shows marked Bauschinger and elastic after effects, and internal stress by which they are induced, brings about room temperature age hardening*. Also in high carbon steels, these effects are pronouncedly marked⁷⁾⁸⁾, and internal stress is considered to contribute partially to room temperature age hardening and primary anneal hardening. But with the lower carbon steels the hardening due to internal stress becomes less marked.

Besides, thermal and mechanical treatments may be cited as the stimuli. As shown in Fig. 17, both treatments bring about quite the same results. They are dissimilar only in that in the former, the destruction of deformation structure is caused by thermal diffusion, while in the latter, it is caused by forced deformation.

3. The correlation of the change in hardness with different mode- secondary working (Figs. 16 and 17), strongly supports the views that when primary and secondary workings are severely made, in any case, the structure specific to the mode of cold working is obtained, it showing a marked anisotropy in anelastic effect, and in the intermediate stage where the as primary- worked structure transforms to the secondary, an isotropic structure is brought about. In accordance, as the secondary working proceeds, a specimen initially hardens and then softens. Secondary work hardening is marked in α solid solution of copper alloys, while in carbon steel, it is less marked than anneal hardening. With reference to this, there are two possible causes, namely,

(1) The intermediate structure as described above is difficult to obtain, and the as primary- worked structure easily transforms to the secondary with the progress of secondary working.

(2) As the cause of anneal hardening, the effect of carbon diffusion is considered besides the destruction of deformation structure. The diffusion of carbon atoms to more stable locations such as vacancies may bring about a rise of yield point in the working direction. Although the temperature range of the rise is somewhat lower than that of secondary anneal hardening (Fig. 6),

* Reference (5) Fig. 9

the rise may contribute to this hardening partially.

4. The secondary anneal hardening in the range of $150\sim 340^{\circ}\text{C}$ is considered to take place near the phase boundaries. Since in this range carbon atoms are considerably easy to move, the internal stresses in the ferrite and vacancy aggregates near the phase boundaries are released by the diffusion, leading to the disappearance of anisotropic deformation structure and thus to a hardening.

Also, a hardening due to migration of vacancies^{19) 20) 21)} may be expected to occur in this temperature range. In α brass, vacancies are created in large numbers during cold work and may form aggregates or stacking faults, which show anisotropic arrangement and shape depending on working condition. Such vacancies cause back stress, by which a marked Bauschinger effect is induced. On low temperature annealing, the migrations of vacancies and zinc atoms cause the removal of this effect and thus a hardening. Also in carbon steel, the migration of vacancies may affect the hardness in a similar manner.

5. The facts that when the tempering temperature is low, upper yield point is absent, and that the work softening effect of tempered steel is directional, judged from both the change in hardness and tensile stress-strain relationship, may lead to the presumption that the softenings after tempering and after anneal hardening treatment may both even arise from the same cause.

The finer the cementite particles the higher the internal stress within the particles¹⁶⁾, and thus the more the dislocation loops, by which back stress is induced. Hence, with a tempered carbon steel of fine structure, the work softening is brought about even by an application of slightly higher stress than the yield.

When cementite particles in a given steel are too fine, dislocation lines are difficult to curve, the work softening being probably less marked. The degrees of work softening and anneal hardening in tempered carbon steel increase more markedly as the tempering temperature becomes low until 450°C as shown in Fig. 18, but below 450°C , the rate of increase becomes progressively smaller. Consequently, there will be an optimum tempering temperature, at which the degrees are at a maximum.

(6) Since the hardness of cold worked steel is particularly sensitive to secondary working as already stated, the degree of secondary anneal hardening is widely different for different methods of measurement. For instances, in the measurement of hardness a heavily rolled specimen shows only a value of 15 ~20% of the degree at most, but in that of bending strength it shows a much higher degree. Also, if the degree of cold working initially received by the specimen is considerably small, the anneal hardening may not be detected

by the measurement of ultimate tensile strength, because the tensile working applied upon the measurement becomes severe and as the result the effect of low temperature annealing is removed.

VI Summary

In carbon steel anneal hardening occurs in two stages on annealing after cold work, of which the primary anneal hardening at about 100°C , seems to be reasonably explained by Cottrell's mechanism. So, study on the secondary anneal hardening in the range of $150\sim 340^{\circ}\text{C}$, has been chiefly carried out and the conclusions obtained are as follows.

1. The degree of secondary anneal hardening increases with increasing the carbon content, this hardening being considered to be associated with the phase boundaries rather than the ferrite itself.

2. A rise of yield point corresponding to the secondary anneal hardening could hardly be detected upon measuring under a stress the same in kind and direction as that of prior working, probably showing that this hardening is due to the elimination of Bauschinger effect similarly to the case of α brass.

3. A slight application of secondary working differing in mode from the primary, causes a considerable hardening, say, secondary work hardening. Anneal hardening seems to be brought about not only by low temperature annealing but by a mechanical treatment.

4. When tempered carbon steel is cold worked slightly, softening occurs. This softening appears to be essentially due to the same cause as the work softening after anneal hardening treatment.

5. Secondary anneal hardening is considered to be induced by the destruction of such a deformation structure as exhibiting a marked anisotropy in anelastic effect. The destruction may be brought about by internal stress, thermal diffusion and cold working. Here, the deformation structure is inferred to be such that cementite particles and vacancy aggregates present anisotropic arrangement and shape depending on working condition, and dislocation loops created around them during cold working show back stress. By low temperature annealing migrations of carbon atoms and vacancies are induced, causing the relaxation of back stresses, and thus a hardening.

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炭素鋼の焼鈍硬化に関する研究

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炭素鋼を冷間加工後焼鈍すると、二段に硬化する。その中、第一段は 150° 以下で起り、低炭素鋼に顕著であって、Cottrell 機構によって合理的に説明出来るようである。

これに反して、 $150\sim 350^{\circ}$ の範囲で起る第二段硬化は高炭素鋼に著しく、又、黄銅の場合と同様に、冷間加工と同種同方向の応力で測定した降伏点の上昇を伴わない。この事実から次のことが推量される。すなわち第二段の焼鈍硬化はフェライト自身よりもむしろ相境界に原因がある。又、この硬化はバウシinger効果の消滅にもとづくものである。そして又、セメンタイト粒子の周囲に作られた転位環が逆応力を呈し、バウシinger効果が顕著になる。転位環の数はセメンタイト及び空格子の凝集体又は積層不整の性質及び形状によって決まる。このような組織が軟化をもたらすが、拡散又は強制変形によって転位環のもたらず逆応力が弛緩し、バウシinger効果の消滅及び第二段焼鈍硬化を起す。